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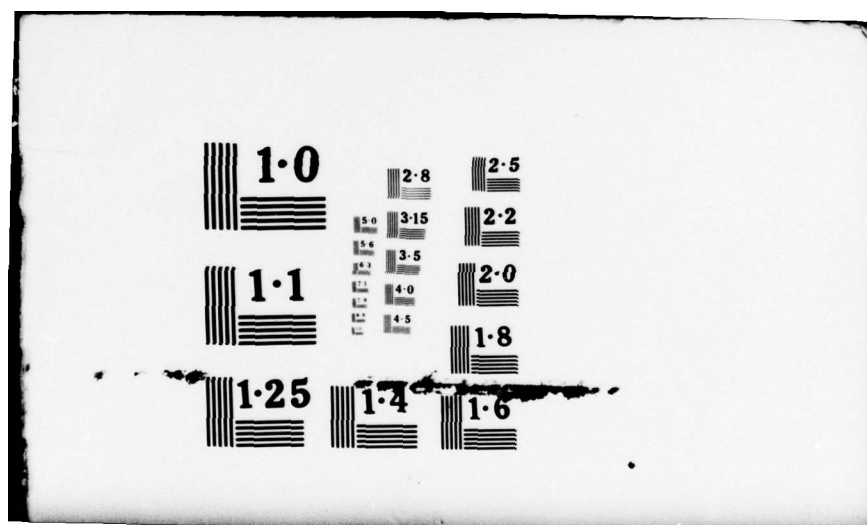
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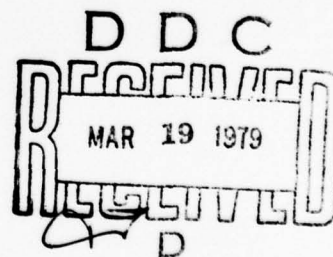
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by

A. N. Panchenkov



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A LIFTING SURFACE OF AVERAGE ASPECT RATIO IN A SUBSONIC GAS FLOW

A. N. Panchenkov

(Kiev)

For many technical applications there must be information on the hydrodynamic characteristics of lifting surfaces of average aspect ratio of arbitrary planform. However, in developing an analytical theory of a lifting surface of average aspect ratio there are difficulties involving peculiarities of the general problem of the motion of a lifting surface in a gas flow.

Methods of the potential of accelerations have made it possible to obtain a two-dimensional singular integral equation for an arbitrary lifting surface under various conditions [1]. Further study

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proceeds along two directions.

1. Development of numerical methods of solving the integral equation. The most widely developed method in various studies is the method of collocations, which in this problem has a simple hydrodynamic interpretation. Distributing discrete vortices along the lifting surface, let us trace the formalistics of the method of collocations; here the number of vortices determines the precision of the solution.

A system of one-dimensional integral equations of the collocation method can be obtained, avoiding operations of the methods of acceleration potential - by examining the physical picture of the flow, caused by Γ -shaped vortices. This method is used in [2] to thoroughly study a broad class of stationary problems of a lifting surface.

2. Development of analytical methods for lifting surfaces of limited planform. The most widely developed theory is that of the Prandtl lifting line - for wings of large aspect ratio - and the theory of low-aspect wings (the Jones theory).

The Prandtl theory is "incorrect" in the limiting sense [7]; in this connection it is not possible to construct, using familiar

methods, a theory of a wing of average aspect ratio in which the Prandtl problem would be the zero approximation. This "incorrectness" in the limiting sense of the Prandtl problem creates mathematical difficulties and has attracted the attention of researchers. For example, M. Van Dyke [8] again turns to this problem and develops a solution based on various expansions and on the connection of the solutions in the problem with "singular perturbations" (using his terminology). The theory of a low-aspect wing is "correct" in the limiting sense, and it can be obtained by passage to the limit from the general problem of a lifting surface [7].

The theory of a low-aspect wing gives satisfactory results only for $\lambda \ll 1$, and its extension to an aspect ratio of ~ 1 and more leads to high errors, particularly in determining the moment on the wing. However, its "correctness" opens the way for development of methods in which the Jones theory will be the zero approximation.

The authors of [4,5] derive a solution to the problem in the form of a series in powers of λ^2 , which does not appreciably expand the boundaries of applicability of the theory.

In [7] we propose seeking the solution to the problem in the form of a series in powers of $r_\lambda = \sqrt{\left(\frac{1}{\lambda}\right)^2 + 1} - \frac{1}{\lambda}$, which can give converging results for a broad range of λ . The results obtained in

this work are encouraging; however, the unwieldiness of the asymptotic methods of the perturbation theory obviously leads to difficulties in developing a theory for wings of arbitrary form.

In the present work we develop an analytical theory of a lifting surface with average aspect ratio, based on the use of integral operators [3] that convert the solutions of the two-dimensional Laplace equation into solutions of elliptical equations. The general representation obtained for the velocity potential includes all the results known from the literature as the zero approximation (a wing in plane-parallel flow, the Prandtl theory, the Jones theory, and the Laidlaw theory of wings of arbitrary aspect ratio [6]). The first approximation, examined in this work, leads to a linear second-order ordinary differential equation for load distribution over the wing chord. This differential equation is easily solved for arbitrary wing planform.

As applications of the general results, in this work we study wings of rectangular and triangular planform. The vast amount of calculation data given in [2] is in good agreement with the obtained results for the intervals of practical interest up to $\lambda \sim 4$.

With an increase in Mach number the limits of applicability of the results increase, and when $M > 0.75$ they are valid to $\lambda \sim 10$.

This fact, in particular, leads to the conclusion that for high Mach numbers even high-aspect wings must be studied using the theory of wings of average aspect ratio.

The problem of the stationary movement of a lifting surface in an incompressible fluid reduces to the boundary-value problem for the Laplace equation:

$$\begin{aligned} \Delta \varphi &= 0; \\ \varphi_x &= F(g); \quad g \in s_1; \\ \varphi_x &= 0; \quad x, y, z \in s_2, \end{aligned} \quad (1)$$

where s_1 is a surface moving in a fluid without perturbations, coinciding with the projection of the lifting surface onto plane Oyx ;

s_2 is a semi-infinite surface moving in a fluid without perturbations and beginning at the trailing edge of surface s_1 .

Using the basic idea of Bergman's method [3] of the possibility of representing the solution to an elliptical equation in terms of the solution to the Laplace equation, for solving the Laplace equation in three-dimensional space we can write the representation

$$\begin{aligned} \varphi &= F_g(y) \left[\varphi_{0g}(x, z) + \sum_{n=1}^{\infty} \varphi_{ng}(x, z) L_{ng}(z) \right] + \\ &+ P_m(x) \left[\chi_{0m}(y, z) + \sum_{k=1}^{\infty} \chi_{km}(y, z) Q_{km}(z) \right]. \end{aligned} \quad (2)$$

Here φ_0 and χ_0 are solutions of the two-dimensional Laplace equation.

Series (2) contains familiar theories as lower-order approximations:

- 1) $\phi = \phi_0(x, z)$ - plane-parallel flow;
- 2) $\phi = F(y)\phi_0(x, z) + \chi_0(y, z)$ - Prandtl theory of a high-aspect wing;
- 3) $P(x)\chi_0(y, z)$ - theory of a low-aspect wing;
- 4) $\phi = F(y)\phi_0(x, y) + P(x)\chi_0(x, y)$ - Laidlaw theory of a wing of arbitrary aspect ratio [6].

Let us state the problem about the realization of the algorithm used to calculate series (2).

In coordinates $\bar{x}, \bar{y}, \bar{z}$ the Laplace equation will have the form

$$\Phi_{\bar{y}\bar{y}} + \Phi_{\bar{z}\bar{z}} + \lambda^2(x) \Phi_{\bar{x}\bar{x}} = 0. \quad (3)$$

The connection among the coordinates is given by the relationships

$$\begin{aligned}x &= \bar{x}b(y); \\ y &= \bar{y}l(x); \\ z &= \bar{z}b(y),\end{aligned}$$

where $\lambda(x) = \frac{l(x)}{b(y)}$ is the relative span in section x ;

$b(y)$ is the half-chord in section y ;

$l(x)$ is the semispan in section x .

If the integral operator realizes the mapping $\Psi(k, \bar{y}, \bar{z}) \rightarrow \varphi(x, \bar{y}, \bar{z})$ and set Ψ is the solution to the equation

$$\Psi_{\bar{y}\bar{y}} + \Psi_{\bar{z}\bar{z}} - B^2(k) \Psi = 0, \quad (4)$$

such an operator will be called the integral Fourier operator.

For equation (4) there exists an integral operator of the first kind with the degenerate kernel

$$\Psi = \Psi_0 + \sum_{n=1}^{\infty} K_n(y) \int_0^y \Psi_0 F_n(y_1) dy_1. \quad (5)$$

where $\psi_0 = C_1$ is the associated solution to the Laplace equation.

We easily find that functions K_n and F_n satisfy the functional relationships

$$-B^2 K'_n(y) F_n(y_1) + K'_n(y) F_n(y_1) - K_n(y) F'_n(y_1) = 0, \quad (6)$$

$$-B^2 + \sum_{n=1}^{\infty} 2 [K_n(y) F_n(y)]' = 0. \quad (7)$$

Let operator T be given in the form

$$T\Psi = \frac{1}{2\pi} \int_0^{\infty} \Psi(k, \bar{y}, \bar{z}) N(k, x) dk, \quad (8)$$

then from (3) we get

$$\Psi_{\bar{y}\bar{y}} + \Psi_{\bar{z}\bar{z}} + \frac{N^*(k, x)}{N(k, x)} \lambda^2(\bar{x}) \Psi = 0; \quad \lambda^2(x) \frac{N^*}{N} = -B^2(k).$$

If function $N(k, x)$ is the solution to the differential equation

$$N^*(k, x) \lambda^2(\bar{x}) + B^2(k) N(k, \bar{x}) = 0, \quad (9)$$

operator T in form (8) realizes the required mapping.

Now we have

$$\begin{aligned} \varphi \equiv T\Psi &= \frac{1}{2\pi} \int_0^\infty \Psi_0(k, \bar{y}, \bar{z}) N(k, \bar{x}) d\bar{x} + \\ &+ \frac{1}{2\pi} \sum_{n=1}^\infty \int_0^{\bar{y}} \int_0^\infty K_n(y) \Psi_0(k, \bar{y}, \bar{z}) N(k, \bar{x}) dk F_n(\bar{y}_1) d\bar{y}_1. \end{aligned} \quad (10)$$

From form (10) we can obtain the second part of series (2), if we set

$$\frac{1}{2\pi} \int_0^\infty \Psi_0(k, \bar{y}_1, \bar{z}) N(k, \bar{x}) dk = P_m(\bar{x}) \chi_{0m}(\bar{y}, \bar{z}).$$

The first part of series (2) can be obtained in the same manner, introducing the operator T_1 that realizes the mapping

$$\Psi(x, k, z) \rightarrow \varphi(x, y, z).$$

Now let us apply form (10) to the problem of the motion of a lifting surface.

If we retain only the first term of series (10), we get an approximation corresponding to the theory of a low-aspect wing.

In accordance with this, we assume

$$\frac{1}{2\pi} \int_0^\infty \Psi_0(k, \bar{y}, 0) N(k, \bar{x}) dk = \frac{1}{2\pi} \frac{1}{\lambda(x)} \int_{-1}^{+1} \frac{\partial \Gamma(\bar{x}, \eta)}{\partial \eta} \frac{d\eta}{(y-\eta)}, \quad (11)$$

where $\Gamma(x, \eta) = \int_x^{+1} \gamma(\xi, \bar{\eta}) d\xi$ is circulation about the contour $L \in [1+x]$ in

section η .

Let us introduce in (11) an assumption typical for a problem only of the class

$$\Gamma(\bar{x}, \bar{\eta}) = \Gamma(x) \gamma(\bar{\eta}), \quad \gamma(0) = 1,$$

then

$$\begin{aligned} \Psi_0(k, \bar{y}, 0) &= \int_{-1}^{+1} \frac{\gamma'(\bar{\eta})}{(y - \bar{\eta})} d\eta G(k); \\ \frac{\Gamma(\bar{x})}{\lambda(\bar{x})} - \int_0^{\infty} G(k) N(k, \bar{x}) dk. \end{aligned} \quad (12)$$

Formula (11) defines the values of the induced velocity along axis z on the lifting surface. Defining the induced velocity from (10), we get the one-dimensional singular integral equation of the problem

$$\begin{aligned} \frac{1}{2\pi} \int_{-1}^{+1} \gamma'(\eta) \left[\frac{\Gamma(\bar{x})}{\lambda(\bar{x})} \frac{1}{(y - \bar{\eta})} + \sum_{n=1}^{\infty} \int_{\bar{y}_1}^{\bar{y}} \frac{F_k(y_1)}{(y_1 - \bar{\eta})} \int_0^{\infty} K_n(\bar{y}, k) G(k) N(k, x) \times \right. \\ \left. \times dk dy_z \right] d\eta = F(\bar{x}, \bar{y}). \end{aligned} \quad (13)$$

Let us examine the problem in the second approximation, retaining in (13) only the terms containing $F_1 = 1$ and $K_1(\bar{y}) = \frac{1}{2} B^1(k) \bar{y}$. From (9) we have

$$B^2(k) = -\lambda^2(x) \frac{N''(k, x)}{N(k, x)},$$

then

$$I = \int_0^\infty K_1(\bar{y}) G(k) N(k, x) dk = -\frac{\lambda^2(x)}{2} \left(\frac{\Gamma(\bar{x})}{\lambda(x)} \right)'' \bar{y}, \quad (14)$$

and the equation will have the form

$$\frac{1}{2\pi} \int_{-1}^{+1} \gamma'(\eta) \left[\frac{\Gamma(x)}{\lambda(x)} \frac{1}{(\bar{y} - \eta)} - \frac{\lambda^2(x)}{2} \left(\frac{\Gamma(x)}{\lambda(x)} \right)'' \bar{y} \ln(\bar{y} - \eta) \right] d\eta = F(x, \bar{y}). \quad (15)$$

Equation (15) can be solved by various approximate methods. In particular, this equation is regulated by the action of the inversion operator in the class of functions unbounded at the ends, and for its solution we can use methods of solving the Fredholm equations. Let us give the solution to equation (15) for a lifting surface with a constant angle of attack over the span in the variational approximation, assuming $\gamma(\eta) = \sqrt{1 - \eta^2}$. Operating on both sides of the equation with the operator $L = \int_{-1}^{+1} \sqrt{1 - \bar{y}^2} d\bar{y}$, we get the differential equation

$$\frac{\Gamma(x)}{\lambda(x)} - \frac{\lambda^2(x)}{8} \left(\frac{\Gamma(x)}{\lambda(x)} \right)'' = F(x). \quad (16)$$

Equation (16) is easily solved with arbitrary functions $\lambda(x)$ and $F(x)$. Thus we can study a broad class of wings with varying

planforms.

As the first example of using this developed theory, let us examine the problem of a plane lifting surface of rectangular planform, for which we have very detailed results obtained by the collocation method in [2].

In this problem equation (16) will have the form

$$\Gamma'(x) - \frac{\lambda^2}{8} \Gamma''(x) = \lambda. \quad (17)$$

The solution to (17), containing two unknown constants, will be

$$\Gamma(x) = \lambda \left[1 + A_1 e^{\frac{2\sqrt{2}}{\lambda} x} + A_2 e^{-\frac{2\sqrt{2}}{\lambda} x} \right].$$

As one of the conditions for determining the constants, let us take the condition of the Joukowski-Chaplygin postulate:

$$\Gamma'(-1) = 0. \quad (18)$$

The second condition can be the condition of the boundedness of the solution with $\lambda \rightarrow \infty$, or the condition

$$\Gamma(1) = 0. \quad (19)$$

From condition (18) $A_1 = A_1 e^{-\frac{2\sqrt{2}}{\lambda}}$ and the solution is transformed to the form

$$\Gamma(x) = \lambda \left[1 - A_1 e^{-\frac{2\sqrt{2}}{\lambda}} \operatorname{ch} \frac{2\sqrt{2}}{\lambda} (x+1) \right]. \quad (20)$$

From the condition of boundedness of the solution when $\lambda \rightarrow \infty$

$$A_1 = e^{-\frac{4}{\lambda} \frac{2\sqrt{2}}{\lambda}},$$

while from condition (18)

$$A_1 = \frac{e^{\frac{2\sqrt{2}}{\lambda}}}{\operatorname{ch} \frac{4\sqrt{2}}{\lambda}}.$$

Now let us define the conditions on the wing.

The lift and moment coefficients of the wing are defined by the formulas

$$C_y = \frac{\pi\lambda}{2} \alpha \Gamma(-1), \quad (21)$$

$$C_m = \frac{\pi\lambda}{2} \alpha \left[\int_{-1}^{+1} \Gamma(x) dx - \Gamma(-1) \right]. \quad (22)$$

Using condition (18), we get

$$C_y = \frac{\pi\lambda}{2} \left(1 - \frac{1}{\operatorname{ch} \frac{4\sqrt{2}}{\lambda}} \right) \alpha; \quad (23)$$

$$e_m = \frac{\pi\alpha}{2} \lambda \left[1 + \frac{1}{\operatorname{ch} \frac{4\sqrt{2}}{\lambda}} - \frac{\lambda}{2\sqrt{2}} \operatorname{th} \frac{4\sqrt{2}}{\lambda} \right]. \quad (24)$$

The position of the aerodynamic center of the wing is defined by the formula

$$x_F = 1 - \frac{\frac{\lambda}{2\sqrt{2}} \operatorname{th} \frac{4\sqrt{2}}{\lambda} - \frac{2}{\operatorname{ch} \frac{4\sqrt{2}}{\lambda}}}{1 - \frac{1}{\operatorname{ch} \frac{4\sqrt{2}}{\lambda}}}. \quad (25)$$

If we determine λ , from the condition at infinity, the lift coefficient will be

$$C_y = \frac{\pi\lambda}{2} \left(1 - e^{-\frac{4}{\lambda}} \right) \alpha. \quad (26)$$

Now we can compare the results obtained with the familiar calculation data.

In Fig. 1, curve 1 represents the results obtained by S. M. Belotserkovskiy for C_y^a [2]; curve 2 corresponds to calculation by formula (26); curve 3 is for calculation per formula (23).

Figure 2 shows a graph of x_F vs λ . Curve 1 represents calculation per formula (25); curve 2 - the results of Belotserkovskiy's calculations [2]. As Fig. 1 shows, formulas (22) and (23) agree well with data for calculation up to aspect ratios of ~ 4 .

We know that the theory of a low-aspect wing gives, for a rectangular wing (see Fig. 1), coincidences with the precise results up to $\lambda \sim 1$ with respect to lifting force, but leads to great errors when determining the moment, even for $\lambda \sim 0.2$. Therefore, conformity of the developed theory with calculation data, with respect to moment, is of great interest. From Fig. 2 we see that even formula (25) reproduces well the displacement of the aerodynamic center of the wing in the set $\lambda \in [0 + 4]$. Formula (26) agrees well with the data in monograph [2] for $\lambda \in [0 + \infty]$. However, determination of λ_1 based on the condition at infinity leads to great errors in determining the moment.

For the subsonic flow of a compressible fluid, in formulas (20) - (26) it is necessary, in place of λ , to set $\lambda_1 = \lambda \beta$ and $\beta = \sqrt{1 - M^2}$, except for the λ appearing with the multiplier in (21) - (26).

It is interesting to note that with increasing Mach number the set in which the obtained results are valid expands, and already when $M \sim 0.75$ $\lambda \in [0 + 10]$.

Now let us examine the problem of a flat delta wing. The function $\lambda(x)$ for a delta wing has the form

$$\lambda(x) = \frac{\lambda}{2} |x|$$

and the general solution to equation (16) will be

$$\frac{\Gamma(x)}{\lambda(x)} = 1 + B_1 x^{a_1} + B_2 x^{-a_2};$$

$$a_1 = \frac{\sqrt{1 + \frac{38}{\lambda^3}} + 1}{2}; \quad a_2 = \frac{\sqrt{1 + \frac{38}{\lambda^3}} - 1}{2}. \quad (27)$$

We determine the constants B_i from the conditions

$$\left(\frac{\Gamma(x)}{\lambda(x)} \right)'_{x=-2} = 0, \quad (28)$$

$$\left(\frac{\Gamma(-2)}{\lambda(-2)} \right)_{\lambda \rightarrow \infty} = 0, \quad (29)$$

$$B_1 = -\frac{a_2 2^{-a_2}}{a_1 2^{a_1} + a_2 2^{(1-a_1)}}; \quad B_2 = -(1 + 2B_1). \quad (30)$$

The lift coefficients for a delta wing will be defined by the formula

$$C_y = \frac{\pi \lambda_\Phi}{2} \Psi a,$$

$$\lambda_\Phi = 2\lambda,$$

where

$$\Psi = 1 + B_1 2^{a_1} + B_2 2^{-a_2}. \quad (31)$$

For the moment coefficient the following formula is valid:

$$C_m = \frac{\pi}{2} \alpha \left[\int_{-2}^0 \Gamma(x) dx - 2\Gamma(-2) \right]. \quad (32)$$

Calculating, we get

$$C_m = -\frac{\pi\alpha}{2} \lambda_\Phi \Psi_1, \quad (33)$$

$$\Psi_1 = 1 - \frac{B_1}{a_1 + 2} 2^{a_1+2} + \frac{B_2}{a_2} 2^{-a_1}. \quad (34)$$

The location of the aerodynamic center of the wing is determined by the formula

$$x_F = -\frac{\Psi_1}{\Psi}. \quad (35)$$

In Fig. 3, curve 1 represents the results of Lawrence's calculations [8], while curve 2 shows the calculations per formula (31).

Figure 4 shows the curve x_F calculated per formula (35). The data obtained for a delta wing give values for $\lambda_\Phi < 2.5$ that are satisfactory for technical applications.

The influence of the Mach number in the delta-wing problem is calculated in the same manner as in the previous problem. Using the developed method we can also study the problem of a lifting surface in a supersonic flow.

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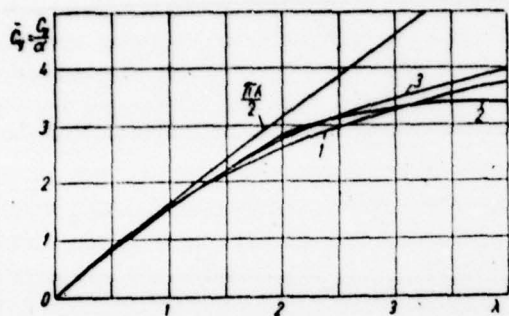


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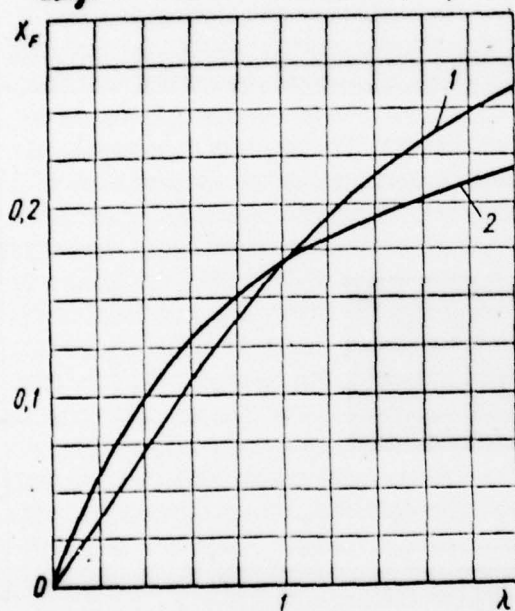


Fig. 2.

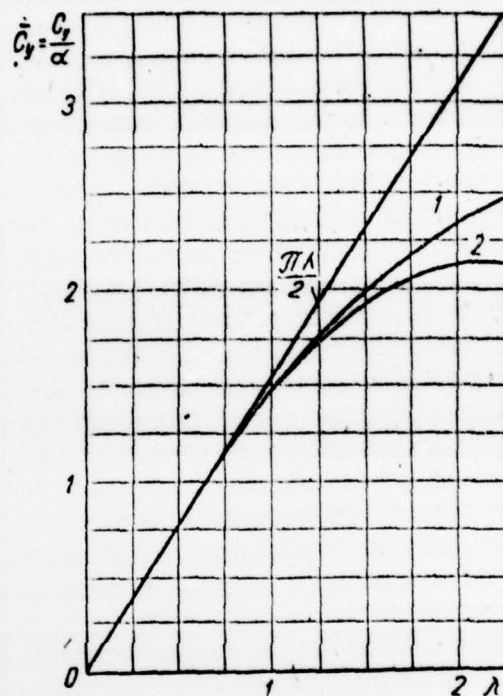


Fig. 3.

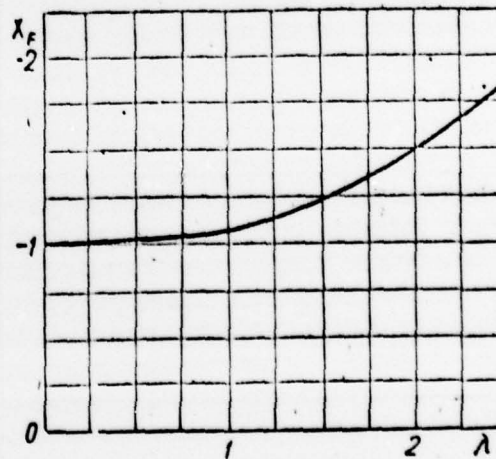


Fig. 4.

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